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APPLIED OPTICS
and
OPTICAL ENGINEERING

EDITED BY

RUDOLF KINGSLAKE

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Rochester, New York

VOLUME I

Light: Its Generation and Modification

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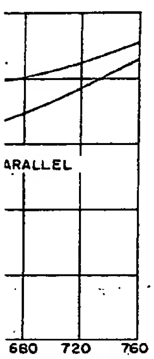

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angle. In some rotating-polarizer modulator arrangements this inhomogeneity can cause "subharmonic" distortion, the areas of maximum density not being 180° apart. The best cure is to use small areas of the sheet and to use the same areas during a complete cycle.

A different form of polarizer is the metallic polarizer. In these sheet polarizers, small needles of metal are oriented parallel to one another. This polarizer works because the absorption of light by the lattice of needles depends on the direction of the electrical vector with respect to the needle axis. One of Hertz' numerous experiments with electromagnetic waves showed that a grating formed of parallel wires is almost opaque to electromagnetic waves when the electrical vector is parallel to the plane of polarization and almost transparent when the electrical vector is perpendicular to them. Hertz' results were extended to the far infrared by DuBois and Rubens.

The mechanical problems of making near-infrared or visible polarizers in this manner are quite formidable. However, a method originated by Bird and Parrish[6] has solved this problem. They have vacuum shadow-cast, with gold or aluminum, the steep face of transmission echelette grating replicas. These replicas, made of polyethylene or polyfluorocarbon, thus have a series of parallel wires on them made of the shadow-cast metal. At wavelengths larger than 4 to 8 times the spacing of the grating, polarization is reasonably complete, and successful polarizers have been made in this manner. Since the untransmitted portion is reflected, the possibility of a sheet polarizing beam splitter exists.

C. Polarization by Double Refraction

Transparent substances fall into two main categories:

(1) Isotropic media in which the velocity of transmission, i.e. the refractive index, is independent of the plane of polarization.

(2) Anisotropic media in which the refractive index in general does depend on the plane of polarization. Anisotropic media are said to be birefringent.

Isotropic media include gases, unstrained noncrystalline solids, liquids, and crystals of the cubic system. Anisotropic media include crystals of the tetragonal, hexagonal, orthorhombic, monoclinic, and triclinic systems, and strained materials.

In general, a beam of light transmitted through an anisotropic crystal is doubly refracted. The beam is divided into two beams, each of which is plane polarized at right angles to the other. Figure 2 illustrates how this occurs.

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[6] G. R. Bird and M. Parrish, Jr., *J. Opt. Soc. Am.* **50**, 886 (1960).

In such anisotropic media there are one or two directions in which light is transmitted without double refraction. A material for which there is one such direction is said to be uniaxial. Such materials are tetragonal or hexagonal crystals. Materials for which there are two directions in which no double refraction takes place are said to be biaxial. The direction, or directions, in which no double refraction takes place is called the optic axis, and it should be emphasized that the optic axis is not a line but a direction.

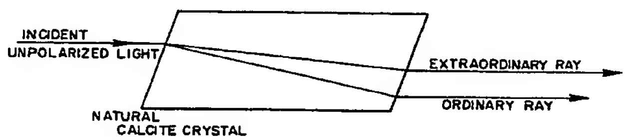

FIG. 2. Double refraction through an anisotropic crystal.

For one of the rays into which a light beam is divided in anisotropic media, Snell's law of refraction is obeyed. This ray is called the ordinary ray. For the other ray Snell's law is not obeyed and the ray is therefore called the extraordinary ray. The extraordinary ray may have a refractive index either higher or lower than that of the ordinary ray.

That the refractive index of an anisotropic material depends on the plane of polarization of the light provides a way of isolating one polarization from another in incident unpolarized light. We may take advantage of the polarization-dependent dispersion of naturally occurring anisotropic media to get polarized light.

The classical way of performing the isolation of one plane of polarization uses an optical device made from a calcite crystal, the Nicol prism, illustrated in Fig. 3. The refractive indices for sodium light of the ordinary ray in calcite, the extraordinary ray, and the balsam cement are, respectively, 1.6585, 1.4864, and 1.54.

The cement, we see, has a refractive index between that of the ordinary ray and that of the extraordinary ray. The extraordinary ray will be refracted at the balsam cement layer and will pass from there on through the crystal. However, the ordinary ray, over an appreciable angular range, will be totally reflected out of the direct beam. The critical angle for total reflection of the ordinary ray corresponds to an angle of about 15° outside the prism. This means that the Nicol prism is not effective as a polarizer in highly convergent or divergent light.

The extraordinary ray also has an angular limit, and beyond this limit the extraordinary ray is also totally reflected. This arises because the refractive index of calcite varies with direction. At some angle the balsam

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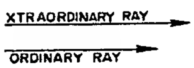

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will have a lower refractive index than that of the extraordinary ray. The prism is cut so that the external limiting angle for the extraordinary ray is the same as the external limiting angle for the ordinary ray, about 15°. The direction of incident light on a Nicol prism is therefore limited on one side to avoid transmitting the ordinary ray, and on the other side to avoid having the extraordinary ray totally reflected.

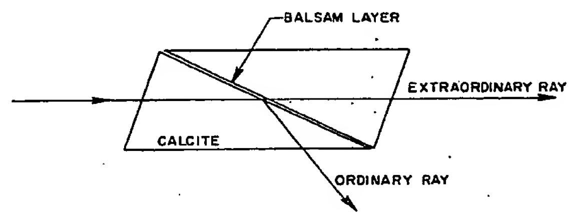

FIG. 3. The Nicol prism.

For separating two mutually perpendicular polarizations rather than for removing one of them, two other prisms are useful. These are the Rochon prism and the Wollaston prism (Fig. 4). With the Rochon prism, the ordinary ray is undeviated while the extraordinary ray is deviated; with the Wollaston prism both rays are deviated.

Prisms of different design from the Nicol are used in different applications. Some are more economical of material by virtue of being more suitable to the shape of naturally occurring crystals of calcite. Some have a wider permissible field angle. Other designs have faces which are perpendicular to the direction of the light and hence are usable in nonparallel light. Still others are suitable for use in the ultraviolet because they contain either no cement or a cement transparent in the ultraviolet.[7-9]

Another kind of construction uses a doubly refracting plate immersed in a suitable liquid. The arrangement is to have the lower index of the crystal lower than the index of the liquid and to mount the crystal at such an angle that the light of the unwanted polarization is critically reflected out of the path. Such an immersed arrangement is fragile but has usefulness because it is conservative of material. It is also useful in the ultraviolet because the amount of absorbing, double-refracting, material in the optical path is reduced. The crystal material used in the ultraviolet is ammonium dihydrogen phosphate.

[7] L. C. Martin, "Introduction to Applied Optics," Vol. I. Pitman, New York, 1930.
[8] R. W. Wood, "Physical Optics," 3rd ed. Macmillan, New York, 1930.
[9] S. P. Thompson, *Proc. Opt. Conv., London, 1905*, p 216 (1905).

Yet another form of birefringent polarizer uses small crystals of birefringent material, the size of the crystals being several times the wavelength. The crystals are suspended in a plastic matrix which has a refractive index equal to one of the principal indices of the birefringent crystals. The sheet is then stretched so that all of the birefringent crystal axes are aligned. The resultant sheet is transparent for one

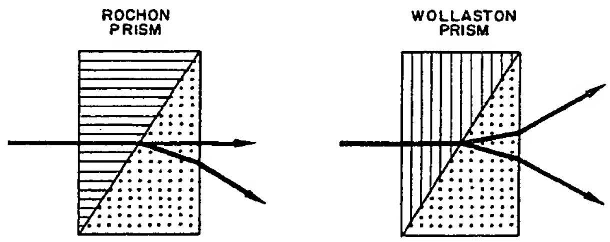

FIG. 4. The Rochon and Wollaston prisms.

orientation of the analyzer, but when the sheet is turned 90° it becomes turbid and highly diffusing. The material acts like a variable diffuser, a diffuser with variable forward gain.

D. POLARIZATION BY SCATTERING

When a beam of light is passed through a suspension of small particles, the light will be scattered by the particles. If the particles are very much smaller than the wavelength of the light, the scattered light will be plane polarized with the plane of polarization being perpendicular to the plane defined by the direction of propagation and the line of sight. If the incident light is plane polarized then no light is scattered parallel to the plane of polarization.

For particles very much smaller than the wavelength, the polarization is complete at right angles to the direction of propagation, and the degree of polarization is given by $P = \sin^2 \theta/(1+\cos^2 \theta)$. Here θ is zero when the source is observed directly and 180° when the observer is at the source. As the size of the particles increases, the direction of maximum polarization generally shifts toward 180° for transparent spheres and toward 0° for absorbing spheres. However, for larger particles the behavior is irregular and exact application of the theory is required for prediction.[10]

[10] H. C. Van de Hulst, "Light Scattering by Small Particles." Wiley, New York, 1957.

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[13] P. Drude, "The T
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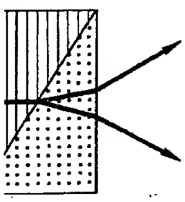

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For different wavelengths, polarization maxima occur at different angles. When scattered light is observed through a polarizer, complicated color phenomena called "polychromism" may be seen. The scattering of light may also be attributed to small density fluctuations in gases and liquids, or to the optical anisotropy of solids.[11]

The scattering of sunlight by the molecules of the air gives rise to the polarization of the light from the sky. The polarization maximum is 90° away from the direction of the sun, and so was proposed by A. J. Pfund as a navigation instrument particularly suited to the long twilights of the polar regions. The invention was anticipated and reduced to practice by the bees, who have been shown to use the phenomenon for navigation.[12]

E. Polarization by Emission

1. *The Polarization of Light Emitted by Continuous Radiators*

By Kirchhoff's laws the emissivity of a body is equal to its absorptivity for any wavelength for any angle of incidence, and for any azimuth of polarization. At other than normal incidence, the reflectance, and hence the absorptivity, of a body depends on the azimuth of polarization of the incident radiation (Section X). It is not surprising, therefore, that the light emitted by a hot body at oblique angles is partially polarized.

For naturally pleochroic substances like tourmaline (Section II, B), the absorptivity depends on the azimuth of polarization of the incident light even at normal incidence. To the extent that tourmaline retains this property at incandescence, it does indeed radiate polarized light when viewed perpendicularly.[13]

2. *The Polarization of Light Emitted as Čerenkov Radiation*

When electrons move through a medium having a refractive index n with a velocity greater than c/n, one observes Čerenkov radiation. This radiation propagates within a cone whose axis is the direction of electron motion. The electrical vector of this radiation lies in the plane defined by the direction of electron motion and the direction of propagation of the radiation.

[11] S. Bhagavantom, "Scattering of Light and the Raman Effect." Chem. Publ. Co., New York, 1942.
[12] R. Ribbands, *Sci. Am.* **193**, 52 (1955).
[13] P. Drude, "The Theory of Optics" (transl. by C. R. Mann and R. A. Millikan), p. 501. Longmans, Green, New York, 1933; also Dover, New York, 1959.

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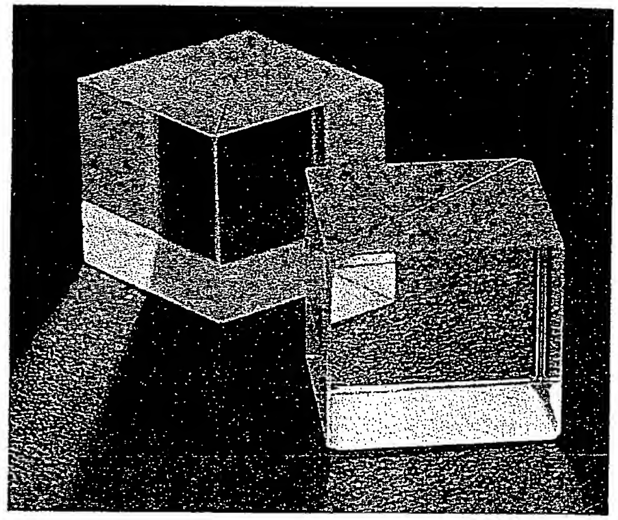
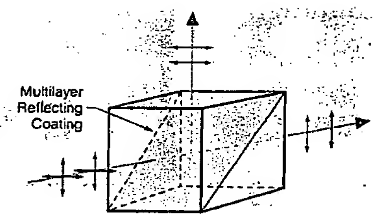


Polarizing Beamsplitter Cubes split randomly-polarized beams into two beams - one is transmitted straight through and the other is reflected internally and emerges from another face of the cube. The hypotenuse face of one of the prism is coated with a multilayer dielectric coating, such that the reflection from each layer is partially polarized and the cumulative effect of the multilayer coating produces a transmitted and reflected beam both of which are highly polarized with the transmitted beam being p-polarized and the reflected beam s-polarized. Two prisms are bonded together with index-matching cement. The entrance and exit faces are antireflection coated.

Narrow Band Polarizing Beamsplitter Cubes

Narrow Band Polarizing Beamsplitter Cubes are cemented components that are optimized for specific wavelengths. They are the best choice for use with single line cw lasers, attenuators, beam combining and clean-up. The angle between the transmitted and reflected beam is 90°.



Narrow Band Polarizing Beamsplitter Cubes

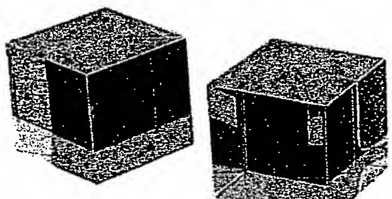
	12.7 mm Cube	25.4 mm Cube
Wavelength (nm)	Catalog Number	Catalog Number
488	44-4380	44-4398
514	44-4406	44-4414
532	44-4422	44-4430
633	44-4448	44-4455
650	44-4463	44-4471
670	44-4489	44-4497
780	44-4505	44-4513
808	44-4521	44-4539
830	44-4547	44-4554
850	44-4562	44-4570
1064	44-4588	44-4596
1300	44-4604	44-4612
1550	44-4620	44-4638

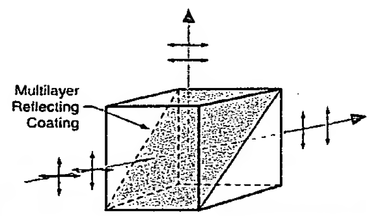
Specifications

Material: BK7 glass
Transmission (p-polarized): >95%
Reflection (s-polarized): >99.8%
AR Coating: R ≤0.25% per surface
Typical Polarizing Bandwidth: 10 nm
Transmitted Wavefront: $\lambda/4$ at 633nm
Surface Quality: 20-10
Extinction Ratio: 1000:1
Dimensions: ±0.2 mm
Clear Aperture: 80% of cube dimension
Laser Damage Threshold
CW: 2 kW/cm²
Pulsed (10 ns): 1 J/cm²

These cubes may be mounted on the Prism Tables shown on pages 394-395

Broadband Polarizing Beamsplitter Cubes





These cemented Polarizing Beamsplitter Cubes are coated to enable operation over a wide range of wavelengths.

The polarization separation is excellent with the transmitted and reflected beams at 90° to each other irrespective of wavelength.

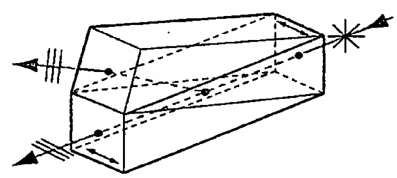
Specifications

Material: SF-2 glass
Transmission (p-polarized): >90% average
Reflection (s-polarized): >99.8% average
AR coating: R <0.5% per surface, 400-700 nm
Transmitted wavefront: $\lambda/4$ at 633 nm
Surface quality: 20-10
Extinction ratio: >500:1
Dimensions: ±0.2 mm
Clear aperture: 85% of cube dimension
Laser damage threshold
CW: 2 kW/cm^2
Pulsed (10 ns): 1 J/cm^2

Broadband Polarizing Beamsplitter Cubes

Wavelength Range (nm)	12.7 mm Cube Catalog Number	25.4 mm Cube Catalog Number
450-700	44-4703	44-4711
670-980	44-4729	44-4737
1300-1550	44-4745	44-4752

Glan Thompson Beamsplitting Prisms



Unlike standard Glan Thompson Polarizers (page 222-223), where the s-polarized ordinary ray is reflected and absorbed, these Beamsplitting Prisms have an additional escape window to allow transmission of the ordinary ray. The escape window is designed such that the beam emerges normal to it ensuring that there is no chromatic dispersion. The p-polarized extraordinary ray is transmitted undeviated from its original path. Coherent Glan Thompson Beamsplitting Prisms have an angular deviation between the two beams of 44° which is not wavelength dependent.

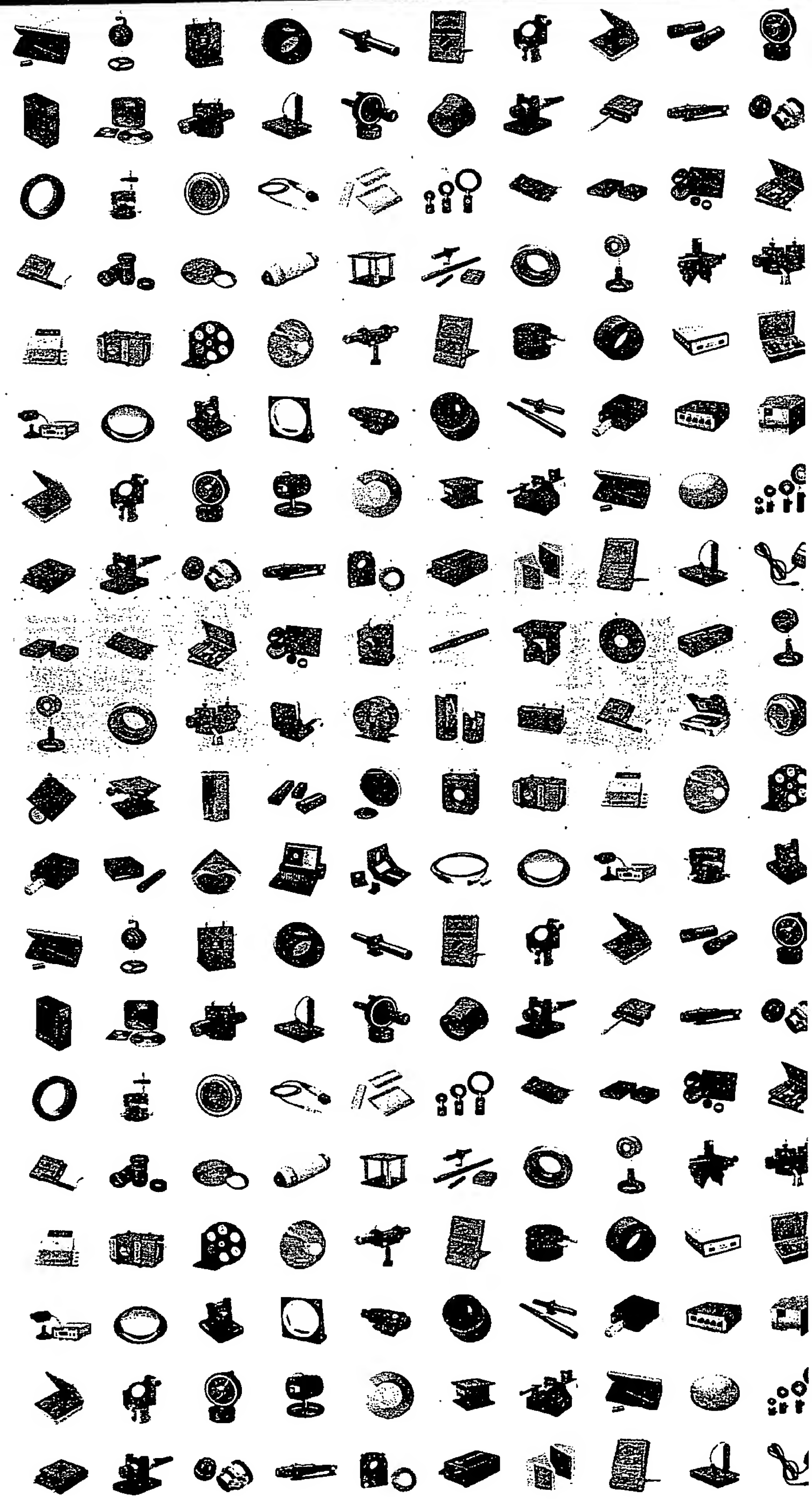
The main applications for these prisms are where there is a need for either a high extinction ratio, a large beam separation or wavelength independence. They are also useful where it is essential that the extraordinary ray is transmitted undeviated. These prisms are not suitable for high power applications. They are supplied mounted.

Specifications

Material: Optical calcite
Wavelength Range: 350-2500 nm
Peak Transmission: 90%
Extinction Ratio: 10^5
Surface Quality: 20-10
Beam Deviation: <3 mins
Dimensions: ±0.1 mm
Laser Damage Threshold: 1 W/cm^2

Glan Thompson Beamsplitting Prisms

Catalog Number	Aperture (mm)	Diameter (mm)	Length (mm)
43-8515	7.0	25.4	36
43-8523	10.0	31.8	48
43-8531	12.0	38.1	49



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